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Steinberger-Wilckens, Robert; Kurban, Zeynep

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CHAPTER 6
FUEL CELLS FOR ENERGY SECURITY

Robert Steinberger-Wilckens – University of Birmingham

Zeynep Kurban – Imperial College London

6.1 INTRODUCTION

Conventional energy supply systems regularly have a hierarchical structure. Electricity or gas are fed in at central nodes and then distributed downwards, into increasingly diverse networks. Large power generation units are implemented to reduce cost and increase efficiency. They are placed at locations of good accessibility to fuel supply (e.g. imported coal) and centres of demand. With a low number of centralised power stations, though, the average distance to the customers grows and so do the losses on the electricity transmission and distribution lines. The relatively low number of generation units increases the impact of the failure of one such unit, which may be followed by major blackouts in the grids [152]. In conventional power generation in thermal generation units, the efficiency can only be increased by building very large (several hundred MW_{el} to GW_{el}) units. Small installations are inherently inefficient [153].

The increase of renewable energy input to the grids is putting on pressure to reform the energy supply structures since renewable energies are often supplied at local level and therefore rather decentralised than centralised – PV home systems being an example of decentralised generation, though offshore windfarms are rather an example of centralised, large scale installations. Increased levels of renewable energy feed-in into electricity and gas supply grids will therefore favour decentralisation of the energy supply. A decentralised grid will be more robust to any kind of interference, be it by natural disasters – such as storms, snow storms, or flooding – or by malevolent interference, such as sabotage, or terrorist attacks, since there is no central unit that can be targeted but a multitude of small installations that will act more like a 'swarm' and may even be empowered to self-organise [154].

Fuel cells, as described in Chapter 4, convert fuels to electricity and heat electrochemically, i.e. avoiding any thermal conversion with the associated pollutant emissions (e.g. nitrous oxides, NOx, particles, sulphur dioxide, SO_2, carbon monoxide, CO, etc.). The efficiency is high since the electricity is directly generated, without any interim conversion steps, such as steam generation in thermal power stations. Furthermore, the conversion process in fuel cells is based on membranes, which makes it fully scalable: the more power is needed, the more membrane surface must be implemented. Therefore, fuel cells in principle retain a high conversion efficiency across a broad range of rated power, with little influence of the unit size, quite contrary to internal combustion engines, or gas or steam turbines.

The reliability of the power grid in the UK has decreased from an average annual outage of 6 minutes/year in 2012–2013 [155], to 15 minutes/year in 2013–2014, 60 minutes/year in 2014–2015 and as high as 9 hours/year in 2015–2016. The supply margin of electricity dropped from 8% to 2% in 2015 [9] (cf. Chapter 5). Developments in other countries, like Belgium and France [156], show that once the large, centralised power stations have to be taken off the grid for maintenance and repair, electricity supply becomes fragile and rationing of electricity results in higher electricity prices for consumers. This will be increasingly the case worldwide since there is a growing reluctance to build large power stations due to financial risk, increasing costs, their inflexibility, and the risks they pose to grid stability [157]. They are also a growing burden on grid power balancing due to the increasing dynamics of the grid load with growing renewable feed-in since the large power stations are all base-load oriented and have only limited capability to respond to load dynamics.

All major grid outages in the last decades in Europe were caused by collapses in the power provided by large power stations, mostly nuclear [152]. Once one unit failed, the repercussions on the grid often led to a second unit being tripped. With the current size of nuclear power stations (generally 1 GW_{el}), a large contribution to the power supply is disconnected when a fault occurs, and the whole power supply balance is tipped.

6.2 DISTRIBUTED POWER GENERATION AND CHP: INCREASING EFFICIENCY

Distributed power supply systems (also known as Distributed Generation or DG) rely on relatively small units (0.7 to some 100 kW_{el}) that feed power into the grid at local level. This reduces grid losses since power generation is located close to where the demand is. The increased number of generation units reduces the probability of losses of high shares of power generation in a single incident. The distributed generation units can be controlled to optimise local power supply, for instance by providing peak power, and the waste heat from electricity generation can be recycled and put to use locally to heat buildings; if the latter is the case, these units are termed ‘combined heat and power’ (CHP). Decentralised systems often are more flexible in the choice of fuels, and the diversity of installations allows for the parallel use of a multitude of fuels.

Heat generation accounts for more than half of global energy consumption and a third of global energy-related carbon dioxide (CO_2) emissions [158]. In the UK, which predominantly generates heat in individual buildings and has only few district heating schemes in operation, heat currently accounts for 78% of total energy consumption [159]. The first White Paper commissioned by the H2FC SUPERGEN Research Hub in 2014 [160] drew attention to the lack of policy on decarbonising heat in the UK and presented the case for how hydrogen and fuel cells can help resolve this great challenge, and how fuel cell CHP systems in particular can create impact in this space.

Fuel cell CHP systems, which provide heat and electricity simultaneously, offer the highest electrical efficiency of any CHP technology, with >60% to AC power for some variants [161], more efficient than large conventional thermal power stations [107] while also enabling local use of waste heat without the need for heat networks. Micro-CHP systems are installed in residential, commercial and industrial buildings. Most of these systems run on natural gas or LPG, but they can be designed to use hydrogen [162]. Even with natural gas, fuel cell micro-CHPs systems can enable 30% reduction in CO_2 emissions [108, 109]. Fuel cell micro-CHP systems could for instance use natural gas efficiently in the short term, run on bio-based gases in the medium term, and then hydrogen from a future pipeline network, as proposed by the UK HFC Roadmap [112].

The Ene-Farm project in Japan has led to the installation of over 180,000 residential fuel cell micro-CHP units between 2012 and 2016 [163]. Units up to 400 kW_{el} are available from U.S./German company FC-Energy, South Korea being the country with the largest installations, up to 59 MW_{el} [164]. With a net electrical efficiency of 50 to 60% they are considerably more efficient than the gas and diesel engine CHP units of conventional design with 29 to 35% and 35 to 45% net electrical efficiency, respectively, depending on size. The higher limit of these ranges is reached at unit sizes of several MW_{el}, the lower for units around 1 kW_{el} which are typical for single family homes. Stirling engine units, which have arrived in the market recently, only reach 10 to 15%.

6.2.1 Resilience of distributed power generation

DG units are gaining an important role in the energy market due to the:

- Reduction of transmission losses (up to 10% energy losses from power station to end user),
- Avoidance or deference of building new electricity lines as local power demand increases,
- Reduction of peak load requirements,
- Inherent support to implementation of CHP schemes, and
- Increased variety of fuels since these units exist in versions running on many different fuels ranging from diesel and natural gas to wood chips and ethanol.

DG units offer more security to the electricity grid by reducing cost and grid losses, improving the reliability of supply, and enhancing access to energy services by offering more choices of fuels [165].

In addition to these points, the application of fuel cells in distributed generation offers further advantages of increased primary energy conversion efficiency (up to a factor of 2). They therefore strengthen the case for the employment of DG units in electricity grids by:

- Considerably improving primary energy conversion in the overall electricity supply system (including reduction of grid losses and increased conversion efficiency compared to existing coal and gas fired power stations, excluding CCGT),
- Offering options for CHP employment starting from single family homes or even single flats up to multi-family blocks of flats, commercial developments, hospitals etc.

It should nevertheless be mentioned that DG systems also bring some disadvantages, namely:

- More complex grid control,
- Issues with grid maintenance safety, and
- Relocation of noise and emissions (with engine based CHP units) from central generation sites to point of use.

Today's trend to 'smart grids' is already addressing the first item by offering all the (IT) technology to embrace increasingly complex energy supply systems. The second item has already become part of grid codes that were implemented to safeguard grid maintenance workers when photovoltaic (PV) systems are connected to a local distribution grid and is therefore today state-of-the-art [166]. Whereas gas and diesel engines can cause substantial issues with pollutant and noise emissions locally, this is not the case for fuel cells, which operate at extremely low noise levels and have a substantially reduced level of pollutant emissions with generally no carbon monoxide (CO), no particles (PM), and very little or no sulphur dioxide (SO_2) and nitrous oxides (NO_x) emitted; nor would they cause any other impact such as vibration or smell of diesel fumes.

Decentralised generation as such does not automatically improve the reliability of the grid. According to the grid code, once a blackout occurs, all generating units connected to the part of the grid that is failing are disconnected [166]. This is done to protect any workers performing repairs from electrical shock and to avoid any aggravation of damages to the grid. The 50 Hz standard for frequency control in the grid is furthermore supplied by central generation units. On the other hand, this is a relic of the times when the major part of electricity supply was still hierarchical 'top down' with little or no local generation. Given a 50-Hz-standard was available (e.g. via internet, radio signal or with a suitable control unit) any building with a DG unit would be able to re-start its electricity supply in 'islanding' mode, i.e. disconnected from the grid. This would substantially improve the reliability of electricity supply and inherently provide back-up or uninterruptible power supply (UPS) which is essential for many commercial buildings, but also increasingly relevant to private homes. With smart grid technology those parts of the grid that are still functioning after a failure in another part (e.g. upstream of a transformer) could be set to islanding mode and the sub-grid restarted using a lead 50-Hz-source. This capability to 'blackstart' is extremely valuable since it avoids much of the cost of grid failures, especially when they occur at a medium voltage level. In these cases large parts of the local distribution grid are affected since the medium voltage grid supplies large numbers of sub-stations. Being able to re-start and run the sub-grids on local generation substantially reduces the loss-of-load probability and thus the level to which critical power supply needs to be backed up with UPS systems. Merely companies with critical IT server operation would still require their own UPS, which, of course, could be supplied by a local fuel cell unit. The company Bloom Energy in the U.S.A. has made a considerable business case for 100 and 200 kW_{el} SOFC units out of the unreliability of the Californian electricity grid, selling over 700 UPS units to date [167].

A system with a fully developed DG would not be safe from technical failures with the individual units. Nevertheless, the probability of losing a major part of the generation at any given time is very low, and the probability of losing 100% of generating capacity is essentially 'zero' [168] as long as not all units are connected to the same fuel supply.

6.2.2 Security challenges of electricity grid operation

Grid outages can occur due to a multitude of reasons, including:

- Wear and tear on the equipment (ranging from cable ruptures to switching gear and transformer failure),
- Unplanned repairs and maintenance on power generation units, or sudden failure of generation equipment or other components of a power station (often the sub-station transformer) with too little replacement capacity being available,
- Incidents with animals, prevalently birds, causing short circuits on overhead lines,
- Impact of foul weather on electricity cables (snow and ice weight load leading to cable ruptures, flooding threatening transformer sub-stations, storms destroying electricity line pylons etc.), and
- Sabotage or malevolent attack on infrastructure (including cyber attacks and terrorism), e.g. by disrupting power lines leading to large generation units, hacking the power station control system, theft of electric cables, etc.

In all these cases disconnecting sub-sections of the grid that are still operational and running them on DG units can limit disruptions and the considerable costs these incur. Following incidents with snow and ice on electricity lines, and extreme weather conditions, sub-grids have been known to be unsupplied for several weeks until lines were finally repaired [169]. This causes high cost and distress for the electricity customers involved.

Fuel cells offer special value with respect to grid survival in that they can be integrated into the lowest levels of power supply – especially residential buildings – due to the lack of noise and emissions, due to their modularity, the high efficiency of conversion, the lack of moving parts that reduce the level of maintenance and repairs, as well as allowing remote control of units such that smart grid technology can be used to rearrange and re-start a sub-grid from an overlooking control unit. This refers to all impacts on the electricity supply infrastructure that disrupt parts of the central generation, and high and medium voltage distribution (points 1 to 3 of above list, and part of point 4). With defects on the low voltage distribution systems down-stream of a sub-station with transformer, it will not be possible to separate the part(s) of the grid that are still functioning due to a lack of switching equipment that were able to single out the defective part. Similarly, any weather incidents, e.g. flooding, that have an immediate impact on the low voltage grid or single buildings will also impact on local DG units. Fuel cell installations are able to overcome this limitation to a certain degree, since due to their modularity, they can be installed in single (residential) buildings. These can be individually separated from the grid and continue operation. A DG unit in this way turns into an uninterruptible power supply (UPS) at little extra cost. This is a decisive 'added value' of micro-CHP fuel cell installations [170].

Allowing the electric utility (or an agency fulfilling the task of grid balancing, such as National Grid) to have access to the system control of the fuel cell 'swarm' will allow the formation of a 'virtual' balancing power station by manipulating the power output of the fuel cell systems according to electricity grid needs. Such a scheme would not be possible with gas and diesel engines due to the considerable noise these would generate when in load following mode with constantly changing RPM. Since fuel cells would be generally operated in CHP mode, the heat storage implemented in such systems would allow de-coupling of electrical power and heat provision, thus allowing electricity generation at times of low heat demand.

Energy infrastructures are essential for the smooth operation of the economy and everyday life; they are today considered at substantial risk from malevolent interference. This can range from local vandalism, up to centrally guided sabotage in wartime or by terrorist act. Centralised systems offer many options to cut energy supply to a high number of companies and citizens in a single action. The considerable attention given to retrofitting nuclear power stations to be able to survive a plane crash are proof to the immediate threats perceived by governments worldwide. Apart from physical impacts by force, the growing interconnection of key control functions by internet (Internet of Things, IoT) has recently been offering much opportunity to interfere with such control units to threaten to cause damage in order to blackmail suppliers and governments into paying ransoms. Although safety levels in power stations are high, the example of the supposed U.S. American/Israeli IT attack on the Iranian uranium plants shows that even military level protection can be overcome if sufficient effort is made and the bounty is attractive enough. In a decentralised system the effort to ‘hack’ generation units multiplies [171], especially when the units are not connected by the IoT. The impact of shutting down a single unit becomes negligible. It has been argued that the potentially lower level of safety and the standardisation of control units (e.g. using Microsoft products as operating systems) in DG units increases the likelihood of successful ‘hacking’ [172]. Though this might be true, it also remains true that such hacking attacks become more complicated and will most probably have a limited impact not comparable to ‘taking out’ a complete large scale power station or transmission line [173].

The decentralised system has the potential to react in the way of a multi-headed serpent, being able to re-establish its function in sub-grids after fending off any IT interference [174]. The combination of DG units with fuel cell technology therefore offers the benefits of higher modularity, bringing more resilience to disruption and thus reliability. Fuel cells supply the benefits of allowing for very low level installations in every building, so that these can be turned into ‘islanding’ micro grids if the main electricity supply fails.

6.3 BALANCING POWER FOR THE ELECTRICITY GRID

With a growing contribution from renewable electricity in the UK and especially Scotland, the fluctuations of solar and wind electricity fed into the electricity grid will have a growing impact. Scotland has repeatedly been able to supply 100% of its electricity demand from renewable sources recently [175]. This fact does not reflect, though, on the necessity to balance demand and supply in the electricity grid at any given moment. Therefore, so-called ‘balancing’ power generation has to be provided to compensate for any discrepancies between momentary load and the electricity generation. Generally, this will be supplied by the 'spinning reserve' of 5% of generation capacity available in all power stations, and in the next step by fast-reacting gas turbines and pumped storage. In the near future their installed capacity, though, will not be sufficient to compensate for the growing number of photovoltaic and wind farm installations. Hydrogen, electrolysers, and fuel cells, though, will be able to provide solutions (Chapter 5).

A distributed 'swarm' of small, micro-CHP DG units as explained above can offer balancing power at little or no extra costs, if combined with smart grid technologies. Fuel cell units can generally follow fast changes in electrical load as the Japanese market introduction programme for fuel cells, Ene.Farm, has proven. Since CHP units in Japan until recently were not allowed to feed back into the public grid, all 180,000 fuel cell systems employed under this scheme operated off-grid, supplying the electricity needs of households directly [163]. Units are not known to have not coped with the extremely dynamic loads of single households.

Once a sufficient density of fuel cell CHP installations has been reached and a tariff system is in place that incentivises the participation of fuel cell owners in such schemes, a high level of response of the overall DG generation capacity to renewable power supply variations can be achieved. The cost of this infrastructure is minimal; it consists of the interconnection interfaces and software, and a favourable incentivising tariff system for the unit owners. The only thing to keep in mind is the potential vulnerability of such a system to external cyber-attack disruption since it relies on an intimate internet infrastructure.

6.4 FUEL FLEXIBILITY

The low power rating of distributed generation units and the large number of units brings an increased variability and flexibility in fuels used. Whilst single large power generation units in the UK will operate on coal, uranium, or natural gas, DG units can use a multitude of fuels ranging from hydrogen, natural gas (NG), biogas (BG, from household and industry wastes, sewage sludge, farm and food wastes, grass cuttings, energy crops etc.), syn-gas (from biomass or waste gasification), synthetic natural gas (SNG) produced from hydrogen and carbon dioxide (Chapter 5), liquid natural gas (LNG), propane and butane, ethanol and methanol, up to wood chips and pellets. Some of these fuels would be provided by pipeline, others require a delivery system such as with heating oil.

Though most combustion engines will be able to cope with the named fuels, switching over from one fuel to the other will not always be possible, especially when solid fuels are considered. Fuel cells generally will be adapted to one single of these fuels. Nevertheless, all gaseous and liquid fuels mentioned are viable fuels for fuel cells with hydrogen being the lowest common denominator for all systems. Low temperature fuel cells such as PEFC and PAFC will rely on high purity hydrogen, and the DMFC on methanol. On the other hand, the high temperature variants (cf. Chapter 4) can also directly convert many hydrocarbons, including any gas mixture containing methane, but also propane and butane, and the two alcohols.

Especially the SOFC type, which is generally considered the most efficient and best suited for stationary applications, is capable of multi-fuel operation though adjustments will have to be made for differing gas mixture heating values and compositions. This will also apply to the MCFC type, though this will not operate on pure hydrogen unless carbon dioxide is added to the reactant gas streams. Combustion engines need fuel support (mostly diesel) when operating on very low heating value fuels that can occur with biogas or other anaerobic digester, landfill, or coal mine gases. Lean, low calorific fuels are no problem for fuel cells.

Fuel cells therefore introduce a complementary element of flexibility and variability to that described in Section 5.3 for hydrogen which cannot be achieved to the same level with conventional engine-based decentralised technologies. They open the door on a much wider choice of fuels with the possibility of introducing many renewable fuels and especially fuels derived from wastes. The option of producing SNG from renewable electricity (as described in Chapter 3 and 5) links this to the existing natural gas infrastructure without the need to establish a full-scale hydrogen infrastructure. SOFC and MCFC will form a link between a multitude of possible fuel feeds, including methane and hydrogen injection to the natural gas grid. They offer high efficiency, and the options (as explained in Chapter 3) to resort to indigenous fuels ('green' gases, such as green hydrogen or SNG, or direct use of raw biogas) without the need for energy imports. These fuel cell units can be adapted to run on any of the above mentioned fuels with relatively low effort, at maximum (re-)placing the fuel reforming unit.

The broadened range of potential fuels, for instance for the transport market, allows the currently narrow focus on oil derivatives to expand to hydrogen and SNG fuels, thus potentially reducing import dependencies.

High temperature fuel cells can be considered as a bridging technology that can build on the existing natural gas grid as well as a possible future 'hydrogen economy'. The same SOFC can be operated on natural gas and hydrogen, with minor adjustments to the operating conditions. SOFC can therefore support a transition from natural gas to gas mixtures, biogas, or SNG without major changes to the energy conversion units. They could help secure the investment in DG units across a fuel transition period from, say, natural gas to hydrogen with a gradually growing amount of hydrogen injected into the grid, without a need to replace end-use devices.

6.5 VERSATILITY OF TECHNOLOGY LINKING ENERGY SECTORS

6.5.1 Linking energy conversion sectors of the energy markets

In Chapter 5 we discussed the potential role of hydrogen in linking different sectors of the energy system. Fuel cell technology similarly offers a cross-platform technology in that the same base technology can be used across the sectors of stationary applications, transport, as well as portable devices. This will in future allow rapid cost degression due to a multitude of applications based on fuel cell stacks and systems made of similar components and materials, allowing suppliers to rapidly ramp up production volume and reduce cost. This aspect is again supported by the variety of fuels fuel cells operate on, again increasing the range of applications and fuel choice.

Conventional energy supply technology for heating, transport, and portable devices differs greatly in nature. Heating boilers would draw on natural gas, internal combustion engines on petrol and diesel, and portable devices on batteries. Fuel cells – across the types that are best suited for specific applications – use the same base technology for all these three fields. Therefore advances in product development, cost reduction, marketing strategies etc. can build on considerable synergies across these markets [106]. Fuel cells therefore link the different energy markets on the energy conversion device side, also leveraging the employment of the wide range of fuels mentioned in the previous section.

6.5.2 Linking fuel supply sectors of the energy markets

Fuel cells offer another degree of freedom to the energy markets that is increasingly attracting interest: if run 'backwards', a fuel cell would theoretically turn into an electrolyser, for instance splitting water into hydrogen and oxygen instead of recombining the two into water. The laws of thermodynamics tell us that this process is fully reversible. And in fact, AFC, PEFC, and SOFC systems have been successfully reversed in conversion direction. Whereas some difficulties exist with the low temperature variants running both in fuel cell and electrolyser mode, SOFC have been proven to be able to operate both ways in the same device.

This behaviour opens up completely new options for integrating fuel cell technology into supply grids with fluctuating renewable electricity input or with high dynamics of loads. The one same SOFC device can be operated as 'solid oxide electrolyser' (SOE) and split product water back into the gaseous reactants [72]. It can therefore act as a balancing element in electricity grids with a potentially lower investment, since only one type of device is needed for two functions. Reversible SOFC (rSOFC) potentially offer very low switch-over time between supplying electricity in times of demand and acting as load in times of excess (renewable) electricity (cf. Chapter 3). The technology is still at a prototype stage but due to the current scientific and technical interest it is expected to be ready for the markets within the years up to 2025. It links into the P2G technologies discussed in Chapter 5.

From the point of view of energy infrastructure the rSOFC element is especially intriguing since it fully links the electricity with the gas market (both ways and not only gas-to-electricity). Renewable electricity can be turned to gas (hydrogen) which can be converted back to electricity (cf. Figure 3.7). Obviously, this would be one option for electricity storage, albeit the round-trip efficiency is today still rather low, between 35 and 65%, depending on type of units employed. SOE can be operated in 'co-electrolysis' mode when carbon dioxide and water are mixed as the feed. The result is a similar syn-gas to what is produced by biomass gasification. Using the methanation technology described in Chapter 3, this syn-gas can be converted to pure methane which is nothing else than synthetic natural gas (SNG). This is fully compatible with the existing NG infrastructures and again forms a bridge between current, polluting technology and a future sustainable energy supply system. Hydrogen, syn-gases from biomass gasification, and co-electrolysis can thus link renewable electricity with hydrogen economy elements and the existing methane (formerly natural gas) infrastructure, as indicated in Figure 3.7.

This allows for a high number of degrees of freedom in transitioning from the current system to a more sustainable future. Access to energy resources is diversified, resulting in a higher security of supply and a higher reliability of the overall system since shortages of one fuel can be quickly compensated for by replacement by another fuel used in the same devices, as long as high temperature fuel cells are considered (cf. Chapter 4). Given the multiple sources hydrogen can be obtained from (cf. Chapter 3), even the low temperature fuel cells have some flexibility in fuel choice as far as the origin of the hydrogen is concerned.

6.6 ENABLING TECHNOLOGY OPTIONS

There are a number of applications where fuel cells play the role of an 'enabling' technology – offering solutions to problems and allowing for applications which were not possible with the incumbent technologies.

The aspects of fuel diversification, access to fuel resources, use of indigenous fuels, emission control, and sustainability are all addressed by fuel cell electric vehicle (FCEV). These are electric vehicles with or without a main battery that are powered by hydrogen driven fuel cells. While the battery will serve to supply the dynamics of driving, the fuel cell will continuously recharge, thus giving the electric vehicle a range that is only limited by the size of the hydrogen tank. FCEV are therefore an enabling technology to make electric vehicles compatible with everyday expectations of range and driving comfort.

FCEV are likewise an enabling technology with respect to zero emission transport. Battery electric vehicles (BEV) are limited in scope and attractiveness by a range that is not fit for today's everyday usage. Although many boast a range that would cover 100 to 200 miles, in reality and especially in winter conditions they will only manage half that distance [176, 177]. Fuel cell technology is the one option to increase the range of BEV by constantly re-powering the battery whilst not causing any local emissions.

FCEV could in principle act as mobile power supplies. They could connect to the grid when parked and act as distributed generation units [4]. Considering the vast amount of power that is installed in motor vehicles – 30 million passenger vehicles in the UK with an average rated electric power of the fuel cell of 20 kW_{el} would be the equivalent of 600 GW_{el}, six times the installed capacity in power stations available today. There are a number of technical and organisational issues related to this idea which make it doubtful it will ever be realised. Nevertheless, the option to power a home from the family car is already offered by Japanese carmakers [178]. This is a facile option to supplying backup power during a blackout (see Section 6.2) with no extra cost at all, apart from the two-way grid interface. It shows that FCEV technology brings a number of uses that could potentially revolutionise the way vehicles and homes are seen. The home turns into a centre of energy demand but also production, e.g. by photovoltaics. The solar electricity can be used to charge BEV batteries and thus not only serve the electricity needs of the home but also supply energy for transport. Likewise the car can support the building energy needs and back them up in case of emergency. It can also deliver power at any other location, be it a picnic, a holiday cabin, or recreational activities. Workmen can profit from the possibility to carry their own power supply with no noise and emission (and nuisance) generated. This could open up completely new ways of handling building sites or any work at remote locations with no grid access (roadworks, forestry, agriculture etc.).

The capability to blackstart following a grid outage, mentioned in Section 6.2, is another ‘enabling’ aspect that allows continuation of electricity supply once grid supply fails.

6.7 CONCLUSIONS

Fuel cells are an inherently decentralised technology since units are rarely larger than 4 MW_{el} and even when such units are pooled to clusters do not currently exceed 100 MW_{el} rating. They also support fuel flexibility, being able to convert a variety of fuels. They can potentially contribute to substantially reducing the vulnerability of the energy supply systems (electricity grid, natural gas grid, transport fuel supply) to political events, market volatility, and malevolent interferences.

Fuel cells will therefore support grid functions with respect to:

- Reduced distribution losses,
- Increased reliability due to lower probability of total disruption,
- Sourcing of balancing power to stabilise electricity grids with high renewable electricity penetration,
- Increased fuel economy, thus reduced operating cost and impact of fuel price volatility, and
- Allowing blackstart capability and the option to ‘island’ those parts of a grid that are still intact following an outage.

Fuel cells also bring new key elements to the energy markets through:

- Increased fuel flexibility by allowing for a variety of new fuels, many of which are generated from renewable energy sources, and
- Offering new applications of technology by using a cross-platform base technology that links stationary power generation with mobile and portable applications, as well as connecting the electricity and gas infrastructures.

Finally, the option to reverse fuel cells into electrolysers opens up new perspectives for renewable electricity balancing and energy storage. Electricity grids with high penetration of wind and solar become better controllable due to the sub-second response of both electrolysers and fuel cells. The increased interaction between gas and electricity infrastructure allows for more degrees of freedom in balancing supply and demand, and it creates synergies between the different energy markets as the links between primary energy feedstock and energy vectors become increasingly flexible.

Introducing fuel cell installations into buildings as micro-CHP units will enable these to continue operation during grid outages. This takes the idea of Distributed Generation a little further since it enables single buildings (and not parts of the grid) to switch to 'islanding' mode. The micro-CHP installations can be combined by internet technology to form 'swarms' of generation units that can replace costly peak load fossil fuelled units in the electricity grid. The 'virtual' generation units can be pooled to deliver considerable peak power.

Employing the same or similar fuel cell technology across a variety of applications (stationary, mobile, portable) leverages cost reductions, by standardisation of components and increased volume of manufacture. Multiplied with the variety of fuels employed for the different fuel cell types, this also brings an added element of fuel flexibility to what was discussed in Chapter 5.

Fuel cells offer customers in certain areas an 'added value' in that they allow completely new applications. Fuel cell vehicles can act as storage device for buildings and renewable energy, as well as generating power for buildings and the electricity grid. In some ways this technology could open up future options similarly to the advent of the smart phone.

In addition to contributing to resilience and reliability of the energy systems, fuel cells also contribute to fuel flexibility (access to energy), reduction of emissions (sustainability), and reduction in fuel use owing to higher efficiencies (affordability), previously discussed in Chapter 5.